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A LATE-PLEISTOCENE PHASE OF SAHARAN DUST DEPOSITION IN THE HIGH APENNINE MOUNTAINS (ITALY) .

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ABSTRACT: The presence of Late Pleistocene hexogen quartz-rich loess on Apennine massifs, formed by limestone rocks, has been reported since the 90s of the 20th century, and indicates that the dust must come from outside areas. The thickness of the aeolian deposits decrease from south to north, becoming null north of the latitude of 42° N; thus indicating that the dust come from South.
The study of new exposures on Mount Matese, where the loess is interbedded with tephra layers and in proglacial lake sediments, have led to a more detailed chronology of the phases of sedimentation. Specifically, we have established that the loess deposition was contemporaneous with the Late Pleistocene phases of intense Saharan dust sedimentation in maar lakes in Italy, and in the Mediterranean Sea.
The geochemical characterization and the recognition of three tephra layers have enabled us to establish that the end of the loess sedimentation occurred at the transition between the Oldest Dryas stadial (or Greenland stadial GS-2) and the Bölling/Alleröd Interstadial (or Greenland Interstadial GI-1), simultaneously with the start of the African Humid Period. We hypothesize, therefore, that the quartz-rich loess in the Apennines was formed by the sedimentation of Saharan dust. The greater amount of dust, brought by southerly winds, would have been sedimented during periods of increased aridity in North Africa which were coeval with the Apennines Last Glacial Maximum and stadial phases.

KEYWORDS: Late Pleistocene, Saharan loess, tephra layers, Apennine Chain, peninsular Italy.

1. INTRODUCTION

The Sahara produces more aeolian dust than any other world desert, and Saharan dust has an important impact on soil formation and sediment cycles (Goudie & Middleton, 2001). Its influence spreads far beyond Africa, due to the great distances over which Saharan dust is transported. Deposition of dust to land surfaces may produce *terra rossa* soils in southern Europe and the Levant (Yaalon & Ganor, 1973; Macleod, 1980; Rapp, 1984) and loess (Rapp & Nihlén, 1991; Stuut et al. 2009).

The present Saharan dust sedimentation in Italy is well known and has been studied at least since the ’50 (Fett, 1958). Southern air masses bring dust of Saharan origin to the northern shore of the Mediterranean Sea and, sometimes, to far northern latitudes (Franzén et al., 1994). Saharan dust sedimentation on the Apennines is easily documented at higher altitudes, where, at the end of winter, the snow contains several thin dust horizons light brown-pink in colour.

On the high mountains of the central and southern Apennines is present a late glacial loess, of the same color of the Saharan dust, , mainly consisting of quartz (Frezzotti & Giraudi, 1990a; 1990b; Giraudi 1997,1998a, 2001, 2004; Zanchetta et al., 2012). Since the massifs on which the loess is present are of limestone rocks, dust quartz-rich must come from outside areas, and the Sahara was considered the possible source region (Giraudi,2011).

The occurrence of Saharan dust in the Late Pleistocene and Holocene sediments of the Italian peninsula has been proposed by Narcisi (2000) which documented the presence of varying percentages of aeolian quartz in the sediments cored in the volcanic maar lakes formed by SiO_2 under-saturated ultra-potassic rocks. The sedimentation rate of quartz has undergone significant changes over time, but the sedimentation has never ceased altogether. Andreucci et al. (2012) also provided evidence for Saharan dust sedimentation during the Late Pleistocene in the island of Sardinia.

The presence of Late Pleistocene and Holocene sediments partially formed by Saharan dust, confirms that, also in the past, Southern air masses have reached the Italian peninsula.

In the present paper new data on the high Apennines loess are reported and some stratigraphic successions are discussed in order to provide a reliable chronological framework and establishing the climatic factors leading the variation of the dust transport and deposition in central-southern Italy (e.g. humidity variation versus southern circulation weakness).

In some sections studied on the Matese Massif (Fig. 1), the quartz -rich loess is interbedded with tephra layers from eruptions of the nearby Phlegrean Fields. The geochemical characterization of three tephra layers, in addition to improve the dating of the sedimentation of the loess, allows us to correlate and synchronize the studied succession with stratigraphic records containing the same tephras.

The dating of the loess also allows a close chronological correlation with some documented phases of

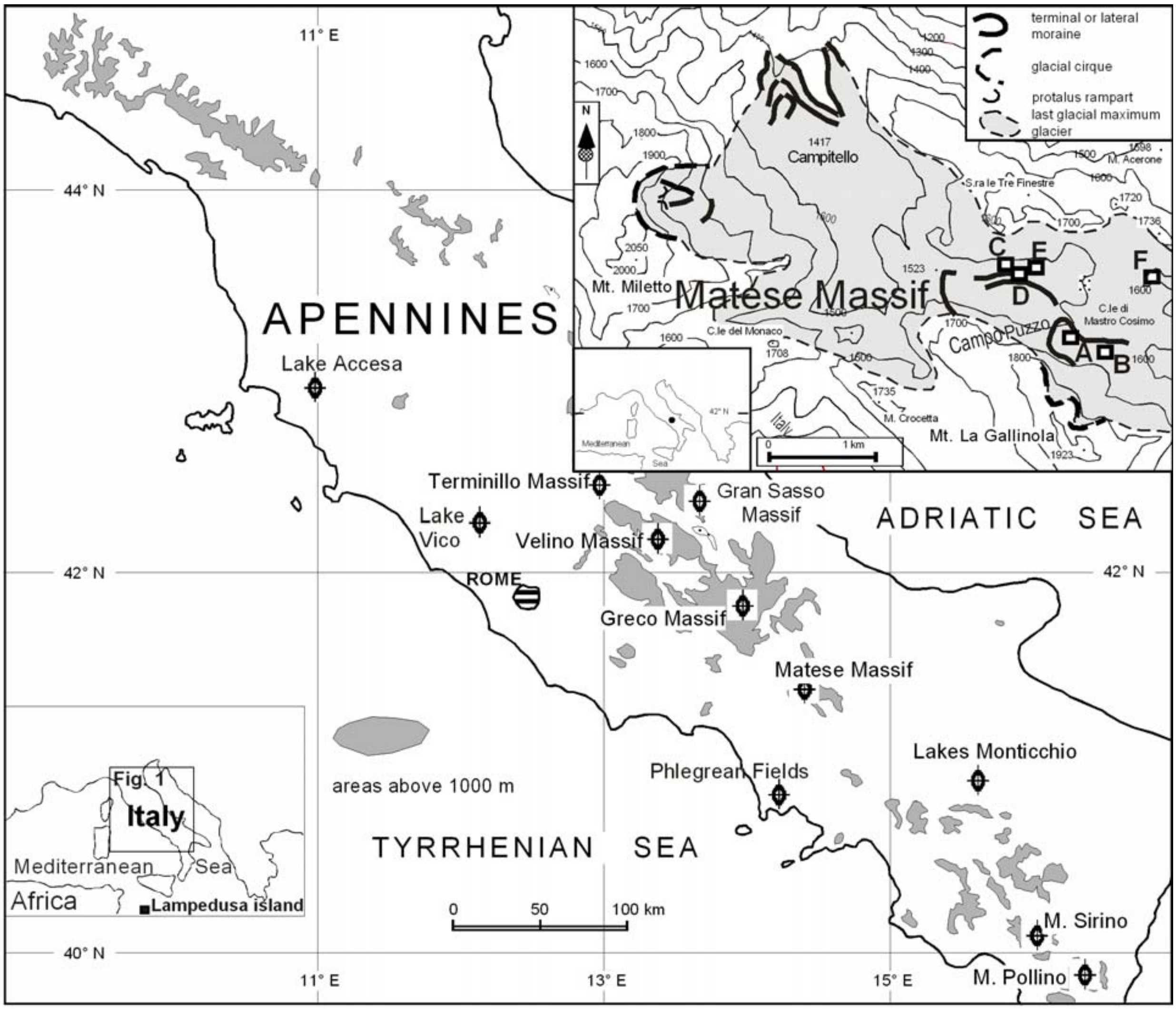

Fig. 1 – Reference map and outline (inset) of the main glacial features and deposits on the Matese Massif . The location of the stratigraphic sections studied is also shown.

increase and decrease in Saharan dust sedimentation in the Mediterranean Sea and the Atlantic Ocean.

2. METHODS

The lithostratigraphic data reported in the present paper were collected by studying exposed sedimentary successions and short cores retrieved through a hand augers.

The studied sites are located above 1400 m a.s.l. in areas glaciated during the local Last Glacial Maximum (LGM) and following stadial phases in some central-southern Apennine massifs, consisting of Meso-Cenozoic limestone. The carbonate composition of the catchment excludes a local source of the aeolian quartz.

Attention has been paid more on the aeolian deposits that cover moraines, formed during LGM or in subsequent stadial phases, or that lie in small retro-morainic closed depressions formed by the melting of dead ice. The choice of these conditions warrant, even in the absence of absolute dating, a reliable correlation with the Late Pleistocene phases of expansion and retreat of the glaciers, which had a primary role in the shaping of the higher Apennine massifs. In addition, the sediments on the summit of moraine ridges may have been formed only by aeolian deposits and tephra layers, while the lacustrine sediments lying inside closed depressions, having an endorheic drainage, can only come from the very small catchments with the contribute of aeolian sediments and tephra layers.

Although the aim of the present study is the dating of the loess deposition, we also report some grain size analyses (performed by Frezzotti & Giraudi, 1990a; 1990b) of the loess from the Matese site A (in Fig. 1), and sites on the M. Greco massif, where the aeolian sediment are better preserved (Fig. 1; 2)

In the other sections, the aeolian origin of the sediments identified as loess is confirmed by the microscopic observation of the quartz grains, which are frosted. Moreover, when sediments are not affected by pedogenesis, field recognition of the loess is quite simple thanks to its colour (in general 7.5YR 4/6, Munsell Soil Colour Chart) which contrast with background of the non-aeolian deposits.

In order to verify the presence of quartz of aeolian origin, the mineralogical composition of proglacial lacustrine sediments has been considered.

The chronology of the phases of aeolian sedimentation is based on the correlation between glacial and aeolian deposits, on radiocarbon datings of organic matter in the sediments, and on the recognition of tephra layers by geochemical methods.

Samples collected in the field for geochemical analyses were air dried, then washed in diluted H_2O_2, filtered and dried in an oven at 40 °C for ca 24 h. The samples were quite rich in glass shards, so no enrichment procedure was performed. The samples were then embedded in epoxy resin and screened for glass shards and micro-pumice fragments using scanning electron microscopy (SEM). Energy-dispersive-spectrometry (EDS) analyses of glass shards and micro-pumice fragments were performed using an EDAX-DX microanalyzer mounted on a Philips SEM 515 at the Dipartimento di Scienze della Terra, University of Pisa, employing a 20 kV acceleration voltage, 100 s live time counting, 2100-2400 shots per second, and ZAF correction. The ZAF correction procedure does not include natural or synthetic standards for reference, and requires the results to be normalized at a given value (which was chosen as 100%). EDS data were calibrated using a combination of well characterized natural minerals (see Marianelli & Sbrana, 1998; Zanchetta et al., 2012). To avoid alkali loss, especially Na, a window spot usually ca 10 μm wide was used. Owing to the different shape and size of the glass shards, a smaller size was sometimes used and this could influence analytical data (Hunt and Hill, 2001). Several trials for comparing the performance of the Pisa SEM-EDS with wave dispersion spectroscopy (WDS) have been extensively discussed by Cioni et al. (1997), Marianelli & Sbrana (1998), Vogel et al. (2010), Sulpizio et al. (2010) and Caron et al. (2010, 2012).

3. RESULTS

3.1. Occurrence of quartz-rich loess

3.1.1. Periglacial deposits of the Central and Southern Apennine massifs

The presence of a loess formed mainly by quartz (up to 70-80%) in the highest central and southern Apennine massifs has been reported by Frezzotti & Giraudi (1990a; 1990b), Giraudi (1997,1998a, 2001, 2004), Zanchetta et al. (2012).

The loess, studied in different exposures and characterized from the mineralogical and granulometric point of view by Frezzotti & Giraudi (1990a; 1990b), always lies at the top of glacial and fluvioglacial sediments matching the post-LGM phases of glacial retreat. The loess sedimentation occurred before the formation of a peat layer dated 16,514-14,280 cal a BP. However, in glacial and periglacial environments subject to erosion and cryoturbation processes, the preservation of Late Glacial aeolian deposits may have been discontinuous. The peat horizon may have been deposited on erosion surfaces. Therefore, the dating of the end of the aeolian sedimentation assumed in the literature remains uncertain. The loess also represent the oldest sediments that fill the dead-ice depressions between the LGM moraines

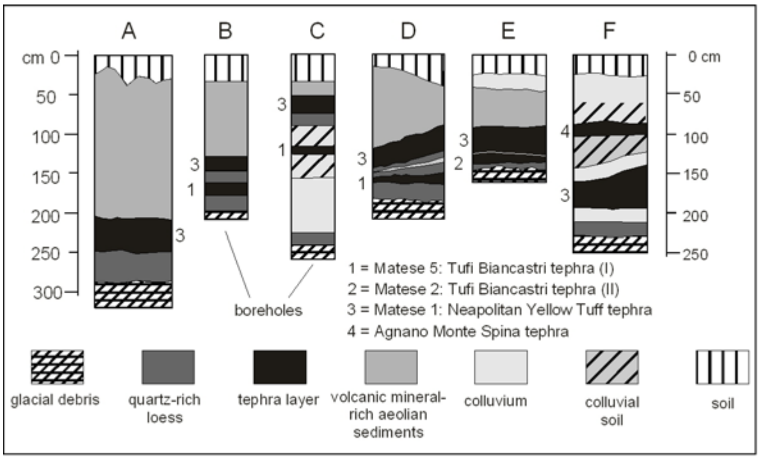

Fig. 2 - The A-F stratigraphic sections studied on the Matese Massif showing the presence of sediments of glacial, aeolian, colluvial origin, tephra layers and soils (site location in Fig.1).

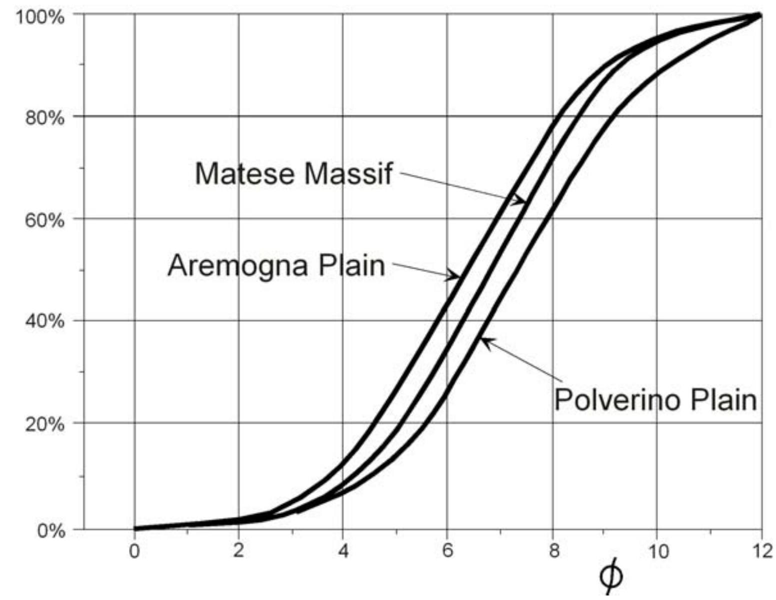

Fig. 3 – Grain size curves of the quartz-rich loess sampled in stratigraphic section A (site location in Fig.1), on the Matese Massif, and in the Aremogna and Polverino Plains, on the Greco Massif. Modified from Frezzotti & Giraudi (1990a; b).

(Giraudi, 2001; Zanchetta et al., 2012).

The new exposures studied on M. Matese (Fig. 2) confirm that the loess formed mainly of quartz lies on LGM and some stadial moraines.

The stratigraphic sections show quite different sedimentary sequences.

The Section A (Frezzotti & Giraudi, 1990a) shows a c. 20 cm-thick layer of aeolian silt, coloured 7.5YR 4/6; the grain size of the bulk sediment (Fig. 3) is those typical of a loess. The loess is made mainly by quartz (about 70%), calcite and phyllosilicates. Excluding quartz, part of the other minerals could have a local origin. In the section A, the loess is covered by the Matese 1 tephra. This tephra, according to Frezzotti & Narcisi (1996) was deposited during the eruption of the Phlegrean Fields known as Neapolitan Yellow Tuff. The tephra is covered by volcanic mineral-rich aeolian sediments.

The loess is easily recognizable because of its colour which is very different from that of the sediments formed by carbonate clasts, i.e. whitish and light brown, and from that of tephra layers and aeolian deposits consisting of reworked volcanic minerals showing different grain-size and mineralogical components and a variety of colours. In addition, in the other sections, the aeolian origin of the sediments identified as loess is confirmed by the microscopic observation of the quartz grains, which are frosted.

The section B (Fig. 1; 2) is formed by blocks of carbonate rocks in sandy silt matrix, which form one of the stadial moraines of M. Gallinola, covered by thinner sediments. The post-glacial sediments have been sampled through a hand auger and are formed by:
- Aeolian silt, coloured 7.5YR 4/6 of the Munsell Soil Colour Chart, 20-25 cm thick; the silt corresponds to the loess of the section A sampled a few hundred metres away;
- Tephra layers, about 10 cm thick, consisting of greenish sandy silt (Matese 5);
- Aeolian silt (loess), coloured 7.5YR 4/6 of the Munsell Soil Colour Chart, 5-15 cm thick;
- Tephra sandy-silty, light green at the base and then grey-yellow, 30 cm thick (Matese 1);
- Volcanic mineral-rich aeolian sediments.

The section C, like the section B, is formed by blocks of carbonate rocks in sandy silt matrix, which form the moraines. The glacial debris is covered by thinner sediments, sampled through a hand auger, formed by:
- Aeolian silt, coloured 7.5YR 4/6 of the Munsell Soil Colour Chart, about 10 cm thick; the silt corresponds to the loess of the section A sampled a few hundred metres away;
- 80 cm of colluvium;
- 25 cm of colluvial soil;
- Tephra sandy-silty, greenish in colour, 10 cm thick (Matese 5).
- Volcanic mineral-rich colluvial soil;
- Quartz-rich aeolian silt, coloured 7.5YR 4/6 of the Munsell Soil Colour Chart, about 10 cm thick;
- Tephra sandy-silty, light green at the base and then grey-yellow, 25 cm thick (Matese 1);
- Volcanic mineral-rich aeolian sediments.

The section D, close to the C section, is an exposure of sandy-silty sediments overlying blocks in sandy silt matrix forming the Campo Puzzo lateral moraines. The sediments are formed by:
- Aeolian silt the silt, 10-15 cm thick, corresponding to the loess of the section A, sampled a few hundred metres away, containing interbedded colluvial horizons, coloured 7.5YR 4/6 of the Munsell Soil Colour Chart;
- Tephra layers, about 5-10 cm thick, consisting of greenish sandy silt (Matese 5);
- Aeolian silt (loess), coloured 7.5YR 4/6 of the Munsell Soil Colour Chart, 5-15 cm thick, containing a thin colluvial horizons formed by phyllosilicates and reworked volcanic minerals;
- Tephra sandy-silty, light green at the base and then grey-yellow, 30 cm thick (Matese 1);
- Volcanic mineral-rich aeolian sediments with a convoluted lamination.

The section E is an exposure close to the D section. The sediments deposited at the top of the stadial moraine are formed by:
- a few centimeters thick aeolian silt, coloured 7.5YR 4/6 of the Munsell Soil Colour Chart; the silt corresponds to the loess of the section A;
- Tephra sandy-silty, grey in colour (Matese 2) about 5-7 cm thick;
- Tephra sandy-silty, light green at the base and then grey-yellow, 25-30 cm thick (Matese 1);
- Volcanic mineral-rich aeolian sediments.

The section F, an exposure about 1 km NE of the sections A and B, is formed by:
- Blocks of carbonate rocks in sandy silt matrix, which form one of the stadial moraines of M. Gallinola;
- Aeolian silt, coloured 7.5YR 4/6 of the Munsell Soil Colour Chart, 10-15 cm thick; the silt corresponds to the loess of the section A;
- colluvial silt, 10-15 cm thick;
- Tephra sandy-silty, light green at the base and then grey-yellow, 30-50 cm thick (Matese 1);
- colluvial sediments and colluvial soils containing a tephra layer. The tephra, identified by Zanchetta et al. (2012), was produced by the Agnano Monte Spina eruption of the Phlegrean Fields, dated to the mid-Holocene.

The difference between the sediments of the studied sections shows that we are dealing with very discontinuous sedimentary successions, as one would expect at high altitudes in a former periglacial environment. In spite of this, the phases of the loess and tephra deposition are generally well recognisable and the difference between quartz-rich and volcanic mineral-rich aeolian sediments is very easy to detect in the field because the colour, the grain size and the mineralogical composition.

The composite stratigraphy of the post-glacial sediments in the studied area is as follows (from bottom to top):
- Blocks of carbonate rocks in sandy silt matrix, which form one of the stadial moraines of M. Gallinola;
- Aeolian silt, coloured 7.5YR 4/6 of the Munsell Soil Colour Chart; in section D the silts contain interbedded colluvial horizons;
- Tephra layers, about 10 cm thick, consisting of green-

ish sandy silt (Matese 5);
- Aeolian silt (loess), coloured 7.5YR 4/6 of the Munsell Soil Colour Chart; in section D thin colluvial horizons are intebedded with aeolian silts;
- Tephra sandy-silty, grey in colour (Matese 2);
- Tephra sandy-silty, light green at the base and then grey-yellow (Matese 1).

The deposition of the loess began before the fall of tephra layer Matese 5 and ended before the fall of tephra Matese 2 and Matese 1.

The sediments deposited after the fall of the Matese 1 tephra are not discussed in detail, but it should be noted that the aeolian sand and silt, consisting of reworked volcanic minerals younger than Matese 1 (Section D, Fig. 2), show a convoluted lamination. These sediments were deformed by cryoturbation processes, already observed on M. Matese by Palmentola & Acquafredda (1983). It follows that the cryoturbation must have occurred in a period of intense cold that followed the fall of Matese 1 tephra, corresponding, according to Giraudi (1997), to the Younger Dryas. In section F, the Matese 1 tephra is followed by colluvia and colluvial soils containing the tephra layer Matese 4 dated to the mid-Holocene.

3.1.2. Lake sediments on other mountains of the Central Apennines

In order to check whether the sedimentation of quartz-rich dust occurred also during the local LGM, some analyses have been carried out on the mineralogical composition of lake sediments of pro-glacial environment.

Microscopic observations and mineralogical analyses carried out on some samples by means of X-ray diffractometry (Anselmi B., unpublished data) evidenced high percentages of quartz (around 20%) in some sediments, found on the Gran Sasso Massif (42°24'N, 13° 38'E) (Fig. 1), dated at about 27-26 cal ka BP by Giraudi & Frezzotti (1997). Also the analyses of the sediments from another pro-glacial lake formed during the local LGM of the most extensive glacier of Monte Terminillo (42°30'N, 12°58'E), with a catchment basin of limestone, reported by Giraudi (1998c), revealed a content of quartz slightly more than 20%. This implies that the aeolian sedimentation on the Apennine mountains began before than previously assumed.

In addition, the dust sedimented at least up to the latitude of M. Terminillo, but the amount was not sufficient to produce distinctive layer to be observed in exposures.

Finally, it is clear that the sedimentation of aeolian quartz was contemporary to the Apennine glacial expansions and retreats.

3.2. Tephrostratigraphy of the Matese samples

The chemical composition of the tephra layers Matese 1, Matese 2 and Matese 5 was determined in order to establish the possible provenance and the correlation with known eruptions and thus to obtain a more precise chronology of the studied successions. The tephra layers considered are interbedded with or lying on top of the loess, and so the correct identification of the tephra layers can enable us to have a chronological constraint for the end of the aeolian sedimentation and for correlating it with other environmental events documented by proxy-data of sedimentary records containing the same tephras (e.g. Lowe, 2011; Lowe et al., 2007; Zanchetta et al., 2011).

MATESE 1 (Lab. Code PI107). It was sampled in the section E (Fig. 1, 2). Chemical composition (Table 1) matches quite well with the compositional variability observed in the Neapolitan Yellow Tuff (Tomilinson et al., 2012), which has been found in distal setting and make this layer quite characteristic for its identification (Fig. 4; Narcisi, 1999; Siani et al., 2004; Wulf et al., 2004; Lane et al., 2011), including the studied area (e.g. Frezzotti & Narcisi, 1996).

Chronology of the NYT is not completely defined. Bayesian integration of dating and stratigraphic information suggest an age for NYT of 14,320-13,900 cal a BP (Blockley et al., 2008). Whereas $^{39}Ar/^{40}Ar$ dating indicate an age of 14.9±0.4 ka (Deino et al., 2004). Lake Monticchio record based on varve counting and extrapolation of sedimentation rate in intervals not varved shows an age of 14,120±710 varve yr BP. These ages are in agreement with the dating of a peat layer below NYT reported by Frezzotti & Giraudi, (1990a). Overall, these ages partially overlap in the 2σ range. Stratigraphically, however, this may be considered within the Greenland Interstadial I (GI-1) in the Greenland event stratigraphy (Siani et al., 2004), as also shown by the pollen data from Lägsee (Austria, Schmidt et al., 2002) and Monticchio (Wulf et al., 2004).

MATESE 2 and MATESE 5 (Lab. Code PI108). The Matese 2 sample was taken in section E, while the Matese 5 sample came from section D (Fig. 1, 2). These levels, on the basis of their stratigraphic position (just below NYT) and homogenous trachytes composition, can be correlated with the so-called Tufi Biancastri (Pappalardo et al., 1999; Tomlinson et al., 2012). Tufi Biancastri have been dated by the $^{40}Ar/^{39}Ar$ method yielding ages between 14.6 ±0.6 and 17.9±0.5 ka. At Monticchio an ash layer correlated with Tufi Biancastri is dated at 14,560±710 varve yr BP (Wulf et al., 2008). These levels also correspond to LN1 and LN2 in the Marine core MD90917 (Siani et al., 2004). In this core the LN1 and LN2 tephras have an age of between ca 13.8 ka to 15.2 ka cal BP. Oxygen isotope curves suggest that LN1 and LN2 tephra deposition occurred between the onset of GI-1 and the end of the Greenland Stadial GS-2 (Siani et al., 2004). Recently these tephra layers seem to be present also at Lake Prespa (Aufgebauer et al., 2012), as in core MD90917 they are probably close to the base of Bölling /Alleröd and one at the transition between the Oldest Dryas and Bölling/ Alleröd. However, these deposits are currently poorly known in terms of age, chemistry and dispersion.

3.2. Other occurrences of quartz-rich loess in Central and Southern Apennine Massifs

The Apennines quartz-rich loess has been identified also in exposed or cored sedimentary succession taken in small depressions associated with Late Pleisto-

Matese 1																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	mean	st dev
SiO2	58.76	61.47	60.7	60.71	60.98	60.66	57.34	57.06	57.82	60.58	60.5	59.6	60.9	58.09	57.31	**59.50**	***1.59***
TiO2	0.6	0.23	0.52	0.4	0.41	0.41	0.56	0.59	0.69	0.5	0.39	0.47	0.46	0.34	0.59	**0.48**	***0.12***
Al2O3	19.3	18.72	19.06	19.77	19.07	19.11	19.29	19.02	19.29	18.88	19.3	19.04	19.01	19.48	19.37	**19.18**	***0.26***
FeOtot	3.85	2.91	3.07	3.43	2.9	3.02	4.87	5.25	4.62	3.16	2.69	3.68	2.85	4.29	4.77	**3.69**	***0.86***
MnO	0.23	0	0.13	0	0.25	0.08	0.13	0.1	0.17	0.08	0.24	0.22	0.24	0	0.16	**0.14**	***0.09***
MgO	0.96	0.72	0.7	0.76	0.5	0.61	1.32	1.76	1.2	0.76	0.82	0.91	0.48	1.35	1.52	**0.96**	***0.39***
CaO	2.99	2.33	2.47	2.45	2.21	2.42	4.12	4.79	3.68	2.43	2.15	2.94	2.19	3.85	4.18	**3.01**	***0.88***
Na2O	4.29	4.27	4.36	4.23	4.62	4.53	3.51	3.37	3.75	4.05	4.2	4.28	4.7	3.89	3.88	**4.13**	***0.39***
K2O	8.48	8.76	8.49	7.67	8.57	8.58	8.35	7.57	8.3	9.07	9.19	8.31	8.61	8.22	7.8	**8.40**	***0.46***
P2O5	0	0	0	0	0	0	0	0.04	0	0	0	0	0	0	0	**0.00**	***0.01***
ClO	0.54	0.59	0.51	0.59	0.51	0.58	0.51	0.44	0.48	0.48	0.53	0.56	0.55	0.5	0.43	**0.52**	***0.05***
Total	100.00	100.00	100.01	100.01	100.02	100	100	99.99	100	99.99	100.01	100.01	99.99	100.01	100.01		
total alkali	12.77	13.03	12.85	11.9	13.19	13.11	11.86	10.94	12.05	13.12	13.39	12.59	13.31	12.11	11.68		
alkali ratio	1.98	2.05	1.95	1.81	1.85	1.89	2.38	2.25	2.21	2.24	2.19	1.94	1.83	2.11	2.01		
Matese 2																	
	1	2	3	4	5	6	7	8	9	10	11	12				mean	st dev
SiO2	61.08	60.93	60.79	60.75	61.23	60.88	60.78	61.11	61.08	61.22	60.78	60.92				**60.96**	***0.18***
TiO2	0.22	0.28	0.44	0.44	0.22	0.43	0.42	0.36	0.42	0.52	0.45	0.35				**0.38**	***0.10***
Al2O3	19.15	19.21	19.21	18.9	19.18	18.93	19.07	19.13	18.89	19.12	19.11	19.14				**19.09**	***0.12***
FeOtot	2.82	2.87	2.95	2.89	2.81	2.95	2.92	2.87	3.02	2.84	3.01	2.79				**2.90**	***0.08***
MnO	0	0.08	0.25	0.24	0	0.2	0.09	0	0.08	0.24	0.16	0.13				**0.12**	***0.10***
MgO	0.53	0.63	0.44	0.54	0.36	0.35	0.57	0.46	0.55	0.49	0.56	0.64				**0.51**	***0.09***
CaO	2.24	2.31	2.16	2.26	2.21	2.31	2.15	2.14	2.09	2.12	2.23	2.23				**2.20**	***0.07***
Na2O	4.79	4.58	4.37	4.43	4.48	4.46	4.62	4.52	4.43	4.51	4.42	4.29				**4.49**	***0.13***
K2O	8.59	8.6	8.82	8.99	8.99	8.96	8.78	8.92	8.86	8.44	8.77	9.01				**8.81**	***0.18***
P2O5	0	0	0	0	0	0	0	0	0	0	0	0				**0.00**	***0.00***
ClO	0.6	0.52	0.58	0.56	0.52	0.54	0.58	0.5	0.59	0.52	0.51	0.5				**0.54**	***0.04***
Total	100.02	100.01	100.01	100.00	100.00	100.01	99.98	100.01	100.01	100.02	100.00	100.00					
total alkali	13.38	13.18	13.19	13.42	13.47	13.42	13.4	13.44	13.29	12.95	13.19	13.3					
alkali ratio	1.79	1.88	2.02	2.03	2.01	2.01	1.90	1.97	2.00	1.87	1.98	2.10					
Matese 5																	
	1	2	3	4	5	6	7	8	9	10						mean	st dev
SiO2	63.33	63.67	62.5	63.42	63.85	63.26	63.58	63.41	63.14	63.51						**63.37**	***0.37***
TiO2	0.38	0.27	0.5	0.4	0.22	0.37	0.27	0.22	0.43	0.38						**0.34**	***0.09***
Al2O3	18.47	18.35	18.77	18.33	18.36	18.19	18.46	18.63	18.91	18.48						**18.50**	***0.22***
FeOtot	2.29	2.42	2.53	2.42	2.26	2.37	2.21	2.39	2.75	2.15						**2.38**	***0.17***
MnO	0.12	0.19	0.16	0.18	0	0.15	0.13	0.09	0.21	0.06						**0.13**	***0.06***
MgO	0.24	0.3	0.33	0.25	0.27	0.41	0.37	0.28	0.24	0.26						**0.30**	***0.06***
CaO	1.45	1.4	1.65	1.47	1.53	1.53	1.52	1.57	1.4	1.53						**1.51**	***0.08***
Na2O	6.14	5.8	5.47	5.88	5.77	6.13	6.08	5.62	5.86	5.94						**5.87**	***0.22***
K2O	6.97	6.91	7.52	6.94	7.17	7.03	6.77	7.21	6.4	7.15						**7.01**	***0.30***
P2O5	0	0	0	0	0	0	0	0	0	0						**0.00**	***0.00***
ClO	0.61	0.7	0.57	0.72	0.59	0.57	0.59	0.59	0.66	0.54						**0.61**	***0.06***
Total	100.00	100.01	100.00	100.01	100.02	100.01	99.98	100.01	100.00	100.00							
total alkali	13.11	12.71	12.99	12.82	12.94	13.16	12.85	12.83	12.26	13.09							
alkali ratio	1.14	1.19	1.37	1.18	1.24	1.15	1.11	1.28	1.09	1.20							

Tab. 1 - Major oxides for the studied tephra.

cene glacial landforms, from Pollino to Velino massifs (Frezzotti & Giraudi 1990a; 1990b; Giraudi, 1997;1998a; 2001; 2004; Zanchetta et al.,2012). Two grain-size analises of the loess (Fig. 3) have been reported by Frezzotti & Giraudi (1990a; 1990b). In the Central Apennines the sedimentary series containing the loess are, generally, formed by:

- LGM or stadial till or glaciofluvial deposits formed by gravel in a whitish calcareous sandy-silty matrix, at the bottom; at the top of the glaciofluvial deposits the matrix is darker and enriched by quartz.
- Quartz-rich loess, formed by silt, coloured 7.5YR 4/6 (Munsell Soil Colour Chart), from a few to 40 cm-thick deposits. Where the thickness of the loess is greater, the sediments at the top are depleted in carbonates which increase toward the bottom. The mineralogical analysis of the sediments has evidenced that quartz is prevalent and that calcite, muscovite and kaolinite are present. Therefore, the minerals are mostly allothigenous. In some places, near the top of the loess there is a very thin tephra layer, formed by glass, K-feldspar, plagioclase, pyroxene and amphibole.

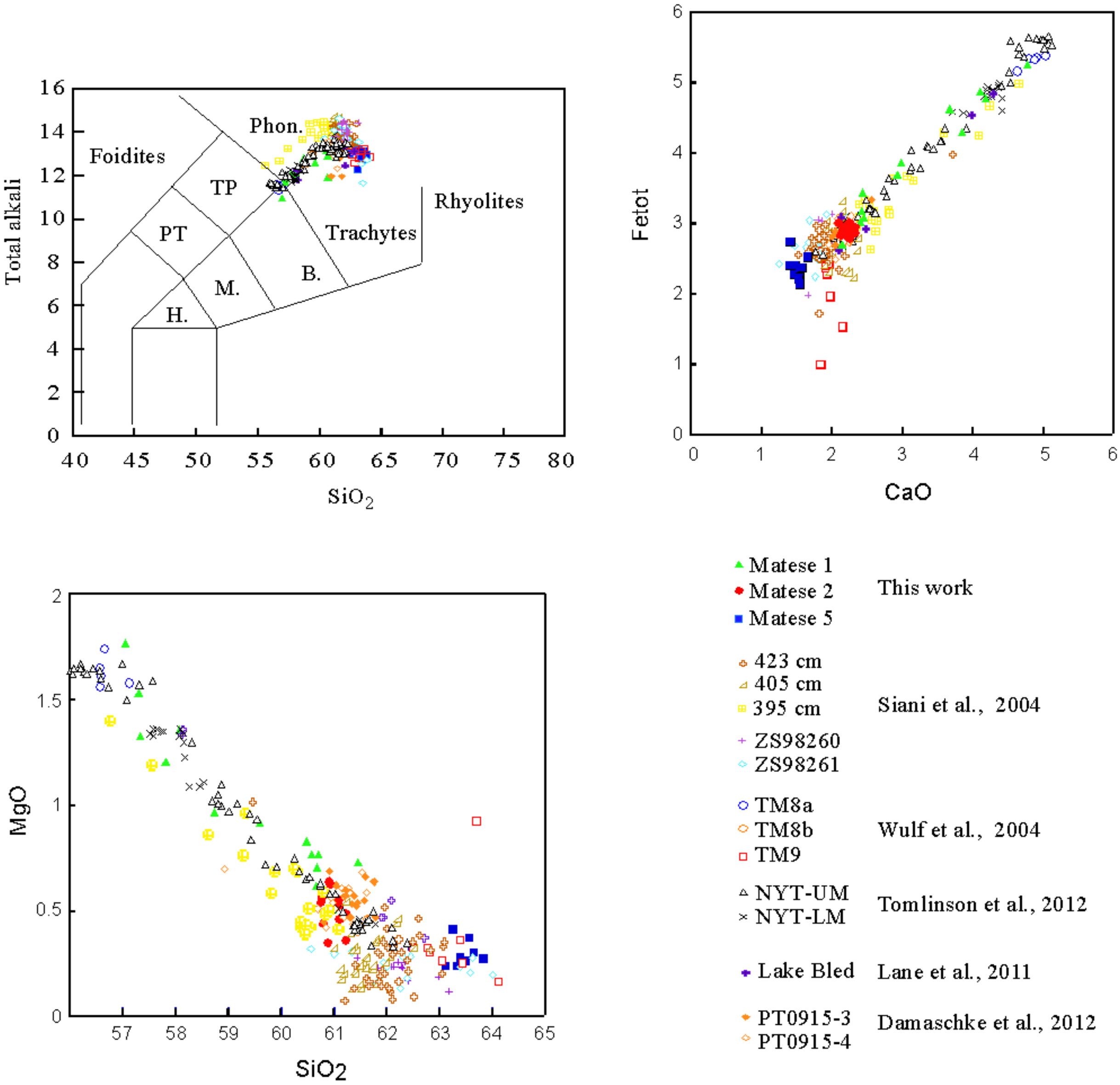

Fig. 4 - A) Total alkali ($K_2O + Na_2O$) vs SiO_2; B) FeOtot vs CaO and C) MgO vs SiO_2, for the samples analyzed. Along with the chemical data for Matese 1 , 2 and 5, the chemical data for TM8a and TM8b for the Neapolitan Yellow Tuff from Monticchio (Wulf *et al.*, 2004, 2008) and TM9 (correlated with Tufi Biancastri) are reported for comparison purposes. Data for ZS98261 and ZS98261 are for samples LN1 and LN2 for proximal data (from Siani et al., 2001, 2004).

- Colluvium made of quartz-rich silt derived from the loess, from a few to 30-40 cm thick. In some cases, interbedded with the colluvium, there is a thin tephra layer, having the same mineralogical composition of the horizon near the top of the loess.
- Tephra layer from a few to 20 cm thick, studied in a number of sedimentary sequences, correlated to the Neapolitan Yellow Tuff (NYT) volcanic eruption from the Phlegraean Fields (Frezzotti & Narcisi, 1996).
- Silt of lacustrine or aeolian origin derived from the re-working of the NYT.
- Alternating soils, lacustrine or colluvial deposits, and tephra layers dated at the Holocene.

The colluvium older than the NYT was not found in the sections where the tephra layer is interbedded with the loess. Therefore, it is likely that the real top of the loess was contemporaneous with the sedimentation of the colluvium. In the Aremogna Plain (Monte Greco massif), at the top of the loess lies a peat layer dated 16,514-14,280 cal a BP (Frezzotti & Giraudi, 1990a).

Summing up, the stratigraphy of the sections where the loess was observed, described in previous papers, is very similar to that studied in the new exposures on Mount Matese.

In the deepest depression of a former glacial cirque on Mount Greco, at an altitude above 2000 m, a

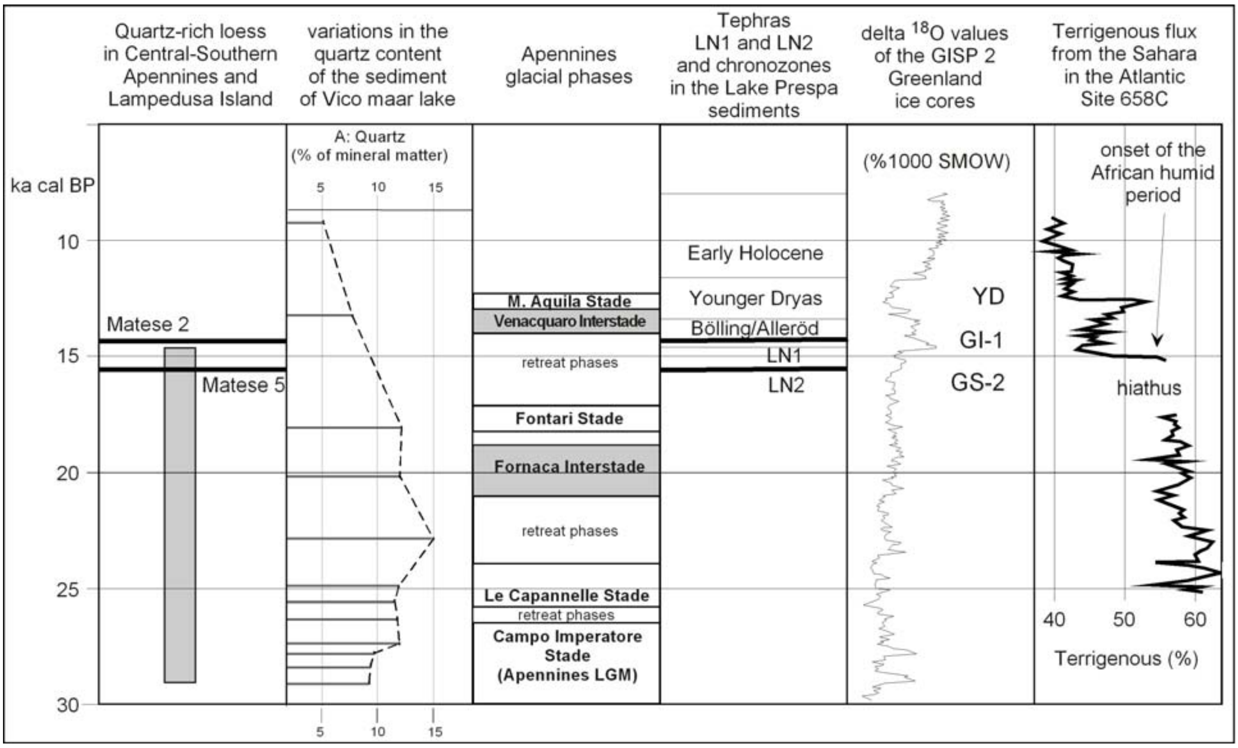

Fig. 5 - Comparison between the phase of sedimentation of the quartz-rich loess on the Apennines, quartz variations in the sediment core of the lake Vico (modified from Narcisi, 2000), Apennines glacial phases (modified from Giraudi, 2012), stadial and interstadial events in Greenland GISP 2 ice core (modified from Grootes et al., 1993 and Svensson et al., 2006), and terrigenous flux from the Sahara in the Atlantic Site 658C (from DeMenocal et al., 2000). The tephra layers Matese 5 and LN2, formed during the Tufi Biancastri older eruption, and Matese 2 and LN1, formed during the Tufi Biancastri younger eruption, are reported and plotted with the quartz-rich loess and the chronozones related to the lake Prespa sediments (from Aufgebauer et al., 2012). Explanation of abbreviations: YD= Younger Dryas; GI-1= Greenland Interstadial 1; GS-2= Greenland Stadial 2.

borehole made using a hand auger showed the presence of the quartz-rich loess, lying on glacial debris, covered by volcanic material and soils. In the same cirque, a fresh layer of quartz-rich silt, up to 7 mm thick, was found by one of us (C.G.) at the end of July 1992, in places partially covering short herbs still alive. The dust probably was deposited during a substantial fall of Saharan dust, in early March 1991, which covered an area of at least 320,000 km^2 stretching from Sicily to the South to Sweden and Finland to the North (Stuut et al., 2009). The dust was probably deposited on the snow and during the melting of the snow accumulated in the cirque depression.

4. DISCUSSION

The set of stratigraphic data and the analysis of the tephra layers show that in the central-southern Apennines the sedimentation of quartz-rich loess began at least 27-26k cal a BP and ended in a period bracketed by the fall of the two Tufi Biancastri tephra layers, that is at the transition between the Oldest Dryas stadial and the Bölling/Alleröd interstadial.

In some areas, a colluvial reworking of the loess deposits occurred during the period just before and after the fall of the older Tufi Biancastri (Matese 5) tephra, and simultaneously with the final stages of aeolian sedimentation. The sedimentation of colluvia implies geomorphological instability, and suggests, as demonstrated in other Apennine massifs (Giraudi et al., 2011), cold climatic conditions. As a consequence, we can conclude that the end of the loess sedimentation occurred before the start of the Bölling/Alleröd interstadial, or, if one refers to the glacial chronology of the Apennines, before the Venacquaro Interstade (Giraudi, 2012).

The quartz-rich loess, for its mineralogical composition, is an exception among the aeolian deposits found in the mountains of the central-southern Apennines.

The other Late Pleistocene and Holocene aeolian sediments found in the same massifs (Frezzotti & Giraudi, 1990a;1990b) have different mineralogical composition. The aeolian sediments, when originated from the deflation of the matrix of fluvial or glaciofluvial deposits, are made up of silt or sandy silt, whitish or light brown in colour, consisting mainly of carbonate. Other aeolian sediments made up of silt and sandy silt, predominantly grey and yellowish or brown in colour, and having quite a varied mineralogical composition, derive from tephra layers or from the degradation of soils containing mostly volcanic minerals.

Late Pleistocene loess deposits are well known in Northern Italy (Cremaschi, 1990; Rellini et al., 2009) but their geographical distribution ends on the northern slope of the northern Apennines. Two loess horizons and interbedded soil have been found on the Adriatic slope of the central-northern Apennines (Chiesa et al., 1990): the younger loess, dated at the Upper Pleistocene was associated with Mousterian artefacts (>40 ka) and therefore older than the loess studied in the present paper.

The thickness of the quartz-loess on the various massifs can be used to trace the origin of air masses. The thickness decreases from south to north (Frezzotti & Giraudi, 1990a; 1990b; Giraudi, 1997,1998a,1998b, 2001, 2004) from a maximum thickness of about 70-100 cm on Mount Pollino (Lat. 39°54'N, Long. 16°12'E) and Mount Sirino (40°06'N, 15°52'E), to 10-40 cm on Mount Matese (41°26'N, 14°24'E), and to 10-30 cm on Mount Greco (41°47'N, 13°59'E). The thickness is reduced to a few centimetres on the Mount Velino (42°13'N, 13°25'E). It is therefore possible to assume that the dust has been transported by air masses from the South.

Today, the dust sedimentation in the Mediterranean and in Italy is produced by the circulation of southern air masses (Guerzoni & Chester, 1996; Guerzoni et al. 1997). According to Prodi & Fea (1979); the proximity of Italy to North Africa and the relief of the Italian peninsula favours the fall of Saharan dust. The air masses bring dust of Saharan origin to the northern shore of the Mediterranean Sea and, sometimes, to far Northern latitudes, as far as Sweden and Finland (Franzén et al., 1994). Present Saharan dusts are made up mainly of quartz, but carbonates, feldspars and clay minerals are present (Lenaz et al., 1986; Nihlén et al., 1995; Guerzoni et al., 1997; Goudie & Middleton, 2001).

During LGM, quartz of Saharan origin were deposited in maar lakes of central Italy (Narcisi, 2000) and the presence of Saharan dust in Upper Pleistocene sediments and soils is also known for the island of Sardinia (Andreucci et al., 2012), at the same latitude as central Italy. According to Stuut et al. (2009) the upper horizon of the *terra rossa* soils in Southern Europe and peninsular Italy (soil zone D1a) is detached from the lower materials because it is made up of Saharan dust, while towards the North (soil zone D1b), the material from Saharan dust is incorporated in the soil system and serves only to increase the fine silt content. For the Italian peninsula, the limit between the soil systems D1a and D1b is indicated at around 42°N, that is the northernmost latitude where the quartz-rich loess has been recognized.

The inflow of Saharan dust in the Mediterranean marine sediments is well known. In the last million years, the influx of Saharan dust has been continuous, but during the glacial periods the quantity of dust was appreciably greater (Dinarés-Turel et al., 2003). Late Pleistocene Saharan dust deposition in the Mediterranean is recognized and dated in marine cores (Eriksson, 1979; Moreno et al., 2002; Bout-Roumazeilles et al., 2007).

The studies carried out on discontinuous stratigraphic successions on the island of Lampedusa, midway between Sicily (Italy) and North Africa (Giraudi, 2004b), show that loess, formed mainly by quartz of Saharan origin, was sedimented at least during the period between 29-28 cal ka BP and 22-21 cal ka BP and during the late Holocene.

The presence of a higher percentage of quartz of Saharan origin during LGM in continuous sediment cores (Fig. 5) from the Lago di Vico and Lagaccione, maar lakes in central Italy, (reported by Narcisi, 2000; 2001; Narcisi & Anselmi, 1998), confirms the data from marine cores, the changing percentage of quartz being due to North African alternating phases of aridity and humidity. Variations of frequency and intensity of southerly winds carrying Saharan dust cannot be excluded.

The reported data on Saharan dust sedimentation in the Mediterranean Sea and in peninsular Italy strongly support the hypothesis that the quartz-rich loess found on the high Apennine massifs was formed mainly by Saharan dust, also if its mineralogy and grain size do not exclude the possibility of a local contribution.

The pollen of African origin, too, studied by Magri & Parra (2002), shows that winds coming from Africa reached the northern Mediterranean shores during some of the periods taken into consideration in the present paper.

Narcisi (2000; 2001) and Narcisi & Anselmi (1998), highlight that during the Late Glacial the sedimentation of aeolian quartz greatly decreased. In particular, at Lago di Vico, the decrease in quartz is dated between 17,866-16,703 and 13,456-12,888 cal a BP, while at Lagaccione it occurred between 16,919-15,847 and 14,138-13,645 cal a BP (radiocarbon dates reported in the papers of Narcisi (2000; 2001) and Narcisi & Anselmi (1998) calibrated using the OxCal 4.2 Programme).

The strong decrease in the quartz of Saharan origin in maar lake deposits corresponds to the end of the sedimentation of loess in the Apennines (Fig. 5).

We think that the only alternative hypothesis on the origin of the loess, e.g. from the continental Southern Italy or from the exposed continental platform, is not reliable. A northern Mediterranean origin of the dust can be excluded because the absence of known atmospheric circulation model that can justify the uplift of a great amount of dust at altitude over 2000 m a.s.l. in the Southern Italy that acted for millennia. If we do not assume a mainly Saharan origin of the loess, we would have to justify and to explain, in terms of atmospherical circulation, the absence of Saharan dust on the Apennine during the LGM and Lateglacial.

An independent confirmation on the Saharan origin of the loess is given by the chronological correlation with the phases of increase and decrease of the aeolian activity in the Sahara. The loess sedimented in the Apennines during LGM and Late Glacial, that is during periods of increased aeolian activity in the Sahara (Fig. 5) reported by DeMenocal et al. (2000) and Swezey (2001). The age of the end of the sedimentation cannot be statistically distinguished from that of the beginning of the African Humid Period, dated around 14-15 cal ka BP according to Gasse et al. (1987), Fontes & Gasse,1989), Gasse et al. (1990), Gasse & Fontes (1992), Cremaschi (1998), DeMenocal et al. (2000), Gasse (2000), Cremaschi (2002). In particular, according to DeMenocal et al. (2000) who studied the aeolian sedimentation in a core taken in the Atlantic Ocean west of the Sahara desert, the African humid period started around 14,850 cal a BP and was synchronous with the end of glacial conditions in Europe and with the end of the Heinrich event 1 (H1) in the North Atlantic, that is, with the end of the Oldest Dryas stadial or the end of Greenland stadial GS-2. The start of the African Humid Period therefore matches the age of the end of the Apennine loess sedimentation.

It is logical to assume that during LGM and late glacial, up to about the end of the Oldest Dryas stadial, or Greenland stadial GS-2, the Italian peninsula was affected by circulation of southern air masses carrying greater amounts of Saharan dust.

The decreased sedimentation of the Saharan dust in the Italian peninsula was probably conditioned by the expansion of the vegetation cover in the Sahara that occurred during the onset of the African Humid Period corresponding to the start of the Bölling Interstadial and, perhaps, by the changes in the circulation of air masses.

The increase of aeolian sedimentation in the Sahara desert and in the Atlantic Ocean cores which occurred during the Younger Dryas (Gasse et al.,1987; Fontes & Gasse,1989; Gasse et al.,1990; Gasse & Fontes,1992; DeMenocal et al., 2000; Gasse, 2000; Swezey, 2001) was not recorded in the high Apennine massifs.

In the Apennines, it is possible that the colluvial and aeolian reworking of the NYT tephra prevented the formation of a layer of loess rich in quartz, but it is also possible that something changed in the atmospheric circulation and that the intensity and the frequency of the southern currents remained lower after the Oldest Dryas-Bölling transition.

5. CONCLUSIONS

The study of new exposures on Mount Matese, in which we recognised a quartz-rich loess with interbedded tephra layers, and the search for quartz in proglacial lake sediments of the Central Apennines, has enabled us to evidence the correlation between sedimentation of the loess and climatic events recorded in the northern hemisphere, and to hypothesize a Saharan origin of most of the dust that forms the aeolian deposit.

This Saharan origin has been proposed according to the mineralogical composition of the loess and to the observed contemporaneity between the sedimentation of loess in Central Apennine highs and of Saharan dust in Central Italian maar lakes and in the Mediterranean Sea sediments.

The geochemical characterization of three tephra layers and their dating allowed us to establish that the end of the sedimentation of the loess was contemporary with the beginning of the African Humid Period and took place at the transition between the Oldest Dryas stadial (or Greenland stadial GS-2) and the Bölling/Alleröd Interstadial (or Greenland Interstadial GI-1). A greater amount of dust, brought by southerly winds, would have been sedimented during glacial stages, corresponding to periods of increased aridity in North Africa.

Although in the Sahara there was a later phase of aridity and an increase of aeolian activity during the Younger Dryas, in the Italian Peninsula loess deposits are either not distinctively recognisable or not deposited, because, in that period, the aeolian sediments were diluted by volcanic mineral-rich sediments resulting from the reworking of the tephra layers, or because the southern currents never reached the intensity or frequency of the period preceding the Bölling Interstadial.

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